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HYDROGEN GAS GENERATOR AS POWER SUPPLY FOR FLUIDIC SEQUENCER

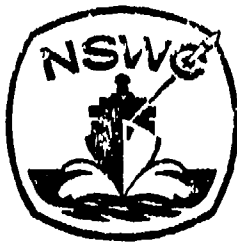
BY W. H. BARBER O. H. DENGEL

RESEARCH AND TECHNOLOGY DEPARTMENT

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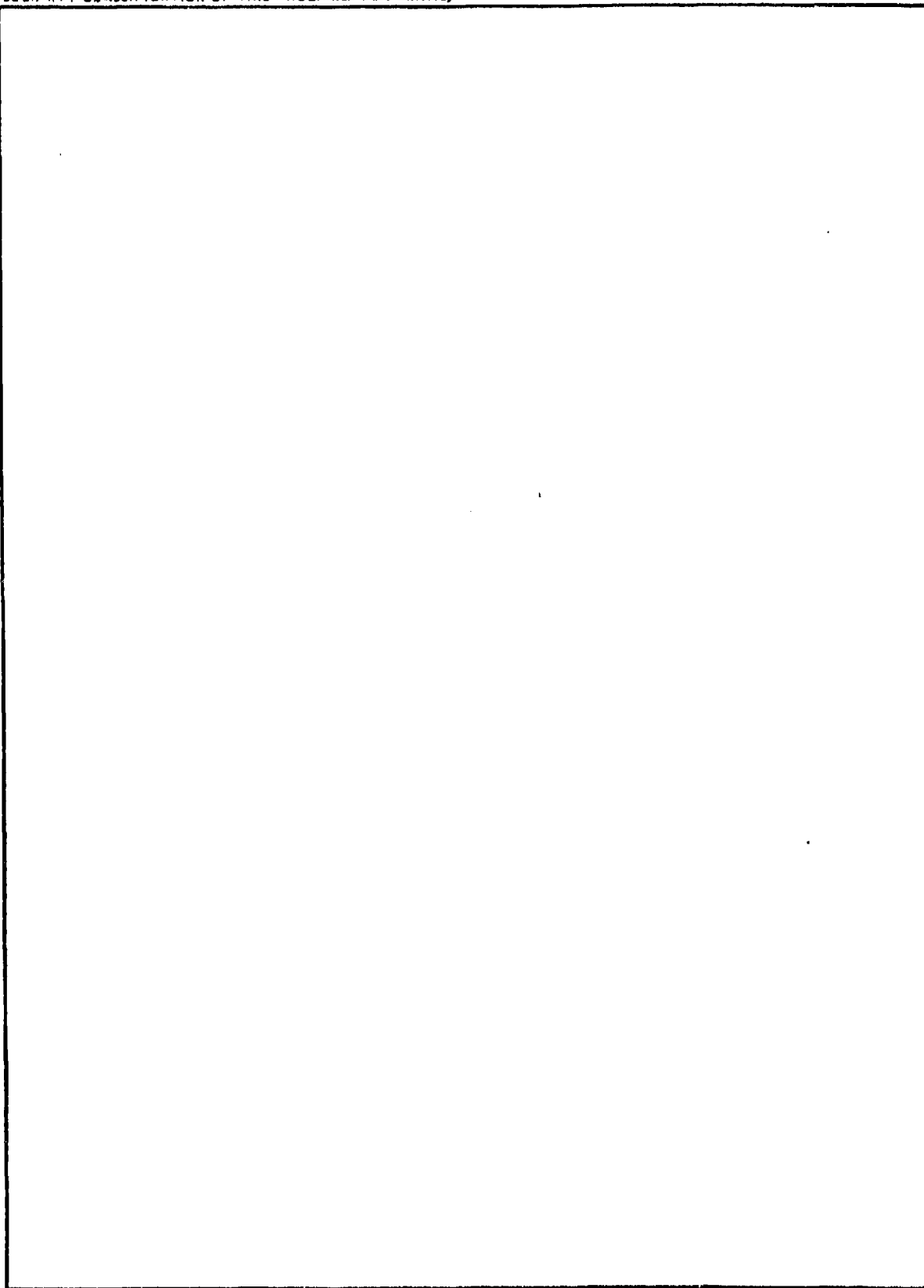
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report summarizes the efforts to develop a hydrogen gas generator for a fluidic event sequencing subsystem (FESS). During the course of this project, not only was a pelletized grain design successfully utilized for the first time, but an entirely new formulation had to be developed to meet the FESS operational and functional requirements. All parameters for the FESS application were met, and only slight modifications in pellet size will be required before interfacing the hydrogen gas generator power supply with the all-up FESS.		

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FOREWORD

This program was performed as part of the development of a Fluidic Event Sequencing Subsystem (FESS) for an Aircrew Escape System (AES). Funding for this effort was provided by the Naval Ordnance Station, Indian Head, Maryland under the Work Request Number N0017478WR80223.

G. L. Mackenzie
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PREFACE

The authors wish to thank K. L. Englander and M. A. Henderson, CAD/PAD Department, Naval Ordnance Station, Indian Head, Maryland for their advice and continuing interest in this project.

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INTRODUCTION

The Naval Surface Weapons Center was tasked by NAVORDSTA to develop a cool gas generator to serve as a power supply for a fluidic event sequencing subsystem (FESS). This fluidic subsystem, in turn, would be used for sequencing and initiation in Aircrew Escape Systems. The operational parameters that must be met by this gas generator are the following:

1. Rise time to a steady state pressure in 25 milliseconds.
2. Sustained output pressure of 5.4 MPa (800 psi) \pm 15% for 5 sec \pm 10% across the temperature range of -53.9°C (-65°F) to +93.3°C (+200°F).
3. A mass flow rate of 3.2 grams/sec hydrogen (35.8 liters/sec @ STP).
4. Particulate size in the output gas shall not exceed five microns, with one micron limit desired.
5. Gas Generator output temperature not to exceed 150°C (302°F) and should be less if possible.

BACKGROUND

Gases can be stored in high pressure cylinders as cryogenic liquids, or in solid form. Storage of hydrogen in liquid or solid form is attractive, because a high volume density can be achieved. However, among the vast number of existing hydrogen containing compounds, only a few exist, which are suitable for hydrogen generation. The many attempts to develop solid hydrogen generators are discussed in references 1 through 7.

The release of chemically bonded or physically absorbed hydrogen requires energy which must be supplied by an external energy source or generated by chemical reactions among the storage matrix ingredients. Within the first category, requiring supply of external energy, fall compounds which can be electrolyzed, such as water, or thermally decomposed, such as hydrazine bisborane, $N_2H_4(BH_3)_2$, or hydrazine, N_2H_4 . The second category, based on internal exothermic chemical reactions, can be subdivided into four groups:

1. Reactions of metals and metal hydrides with acids, bases, water, etc.
2. Reactions of hydrides with hydrates, sulfates, water, etc.
3. Reactions of metal hydrides with metal oxides.
4. Reactions of mixed metal hydrides with ammonium salts.

The mixed metal hydride/ammonium salt reactions such as $\text{NH}_4\text{Cl} + \text{LiAlH}_4 \longrightarrow \text{LiCl} + \text{AlN} + \text{LiH} + 4\text{H}_2$ appear to represent the best compromise regarding thermal stability and heat of reaction. Table 1 shows a family of reactions which have been carefully investigated over a period of 10 years at the Naval Surface Weapons Center.

In the early beginnings of the development of concepts for storage and production of hydrogen by chemical means, the requirement for a low temperature gas suitable for inflation of balloon structures, favored low temperature mixtures such as $1\text{NH}_4\text{Cl}/1 \text{ NaAlH}_4/2\text{LiAlH}_4$ or $1\text{NH}_4\text{Cl}/2\text{LiAlH}_4$. These mixtures have found application in the following programs:

A. THE SINGLE INTEGRATED SIGNAL DEVICE: A hand-deployable signalling device, capable of rocket launching a payload, consisting of a pear-shaped balloon package, a 152 m (500 ft) tether and a gas generator capable of producing 113 liters (4 ft³) of hydrogen in 10 seconds.

B. THE LAND WARFARE LABORATORY SITE MARKER BALLOON: A ground-deployed balloon inflated with 283 liters (10 ft³) of hydrogen from a hydrogen gas generator.

C. THE NUSC MARKER BUOY.

D. THE EODF FLOATATION BAG

E. THE HEL SOLID H₂/D₂

F. THE ARPA SCALE-UP PROGRAM: This program was used to develop the technology and hardware necessary to scale-up from laboratory levels to the point where gas generators producing several thousand liters of H₂ could be manufactured.

G. THE GORJE FUEL MANAGEMENT SYSTEM: This project involved developing a segmented, cigarette burning grain utilizing the $\text{LiAlH}_4/\text{NH}_4\text{Cl}$ formulation. The unit was designed to operate at a pressure of 2.7 MPa (400 psi), producing

1.2 l/sec (0.042 ft³/sec) of hydrogen gas for approximately 100 seconds. The gas was used to pressurize a rubber bladder containing a liquid fuel, forcing the fuel through an orifice into a combustion chamber.

A wealth of technology has evolved from the development of solid hydrogen gas generators for the programs listed above. Generators have been successfully operated in mid-air and at simulated depths of 914 m (3000 ft) in a water environment. As part of the SISD program, gas generators were successfully put through many of the standard environmental and safety tests. During the HEL program a great deal of knowledge was gained on how various catalysts affect the reaction. Unlike normal rocket propellant, the hydrogen gas generator reactant burning rate is largely unaffected by pressure changes in the gas generator. The material will burn at ambient pressures, showing a decrease in burning rate up to 2.02 MPa (300 psi) (see Figure 1) and then a plateau out to 54 MPa (8000 psi) (the maximum pressure at which samples were burned).

Perhaps the only drawbacks of the NH₄Cl/LiAlH₄ formulations are its low burning rate (0.64 to 1.27 mm/sec (0.025 to 0.050 in/sec) depending on the catalyst and its limited thermal stability at elevated temperatures. The low burning rate has led to gas generator designs incorporating pelletized charges. The large surface area of the pellets allows for maximum mass-flow without resorting to eccentric generator hardware designs. Of course, where modest flow rates are required, standard pressed charges of neutral burning configuration can easily be formed. The problem of temperature stability results from the instability of the main ingredient, LiAlH₄, which begins to decompose endothermically at ~125°C (257°F). The complete formulation consisting of NH₄Cl, LiAlH₄, catalyst and binder begins to slowly outgas above 72°C (161.6°F) which is illustrated by figures 2 and 3. The outgassing at ~72°C (161.6°F) is equivalent to a shelf-life of approximately 100 days (50% H₂ loss) at that temperature. In other words, the NH₄Cl/LiAlH₄ formulation can only be used for applications with storage temperatures below 70°C (158°F).

The application of hydrogen gas generators in fluidic subsystems requires a temperature stability of as high as 93°C (200°F). This high temperature can only be achieved by a NH₄Cl/NaAlH₄ formulation at the expense of lower yield and higher gas temperature. Pure NaAlH₄ has a decomposition temperature of 183°C (361°F). The DTA of a NH₄Cl/NaAlH₄ mixture showed a decomposition temperature of ~170°C (338°F) (see Figure 4) which is considerably higher than the decomposition temperature of a NH₄Cl/LiAlH₄ mixture shown in Figure 2. In addition, the NH₄Cl/NaAlH₄ has excellent safety characteristics as summarized in Table 2. Thus, all work on gas generator development for fluidic systems has concentrated with the beginning of January 1979 on exploiting the 1NH₄Cl/1NaAlH₄ reaction. Preliminary tests, prior to this date, were conducted with a 1NH₄Cl/2LiAlH₄ formulation.

SOLID HYDROGEN GAS GENERATOR MIXTURE

INGREDIENT PREPARATION. Preparation of the ingredients for the hydrogen gas generator is no more difficult than for the standard composite propellant. The ingredients are commercially available and can be mixed and pressed according to standard manufacturing technology. The ingredient costs are relatively high (see Table 3) compared to common propellant ingredients. However, as long as the generator is not produced in large quantities, the ingredient costs are relatively minor compared to the manufacturing cost.

Once the ingredients are received from industry, they must be dried, milled, sieved and weighed in preparation for mixing. All of the operations on the hydrides must be conducted in a moisture-free atmosphere. The atmosphere should also be as oxygen-free as possible to decrease the risk of fire. Thus, all manufacturing operations are conducted in "dry" boxes which continuously flush the operating areas with nitrogen, while, at the same time, removing water vapor and oxygen. Not only are all the solids predried, but the toluene is also dried to remove any trapped water.

The weighed ingredients are then transferred to a Baker/Perkins 1 gallon mixer where they are mixed remotely. Like all other operations, the mixer is surrounded by a specially constructed "dry" box to maintain a moisture-free environment. Mixing, generally, requires 1 1/2 to 2 hours per batch, depending on how long it takes to completely remove the toluene solvent. Each mix currently produces 1500 grams of reactant. The finished reactant is sealed in cans and then readied for pressing. Mixing larger batches of reactant would present no great problems, except that a "dry" box would have to be constructed around the mixer. Because of this drawback, the pneumatic mixing process might be the best answer for any future scale-up efforts.

PELLETIZING OF INGREDIENTS. For the fluidics application, a pelletized configuration was selected, because of the high mass flow rate required and the short burn time restrictions. Pelletizing of the $\text{NH}_4\text{Cl}/\text{NaAlH}_4$ formulation required the same precautionary measures as used in the mixing process. Thus, a nitrogen tent had to be built around the pelletizer before pressing operations could commence. A standard Stokes ESD press was used for all pressing operations. This press utilizes 15 stations for pressing with a maximum force of 10 tons. Pellets can be produced in sizes from 3.18 mm (1/8") to 26.99 mm (1 1/16") in diameter at rates from 180 to 335 pellets/minute. The thickness of the pellet can be preset between 3.18 mm (1/8") and 25.4 mm and 1". The only problems experienced in the pressing operation centered around a constant feed rate. This problem was finally resolved by manual shaking of the feed bin. The finished product is a tightly compacted pellet than cannot be broken apart by finger pressure. The pellet size used for this program was 12.7 mm (0.500") L. This dimension was dictated by a burning rate of 0.64 mm/sec (0.025 in/sec) measured

with strand burning samples. Thus, if a pellet burns both ends, it should be consumed in 5 seconds, the required burn time. The pellet size, of course, can be modified to produce whatever flow rates or burn times are desired.

SOLID HYDROGEN GAS GENERATOR HARDWARE

IGNITION SYSTEM. The ignition system for this generator is relatively simple and involves only two items: (1) a small bag of BKNO₃ pellets surrounding an Atlas M100 electric match squib and (2) 101.6 mm (4") strips of heat paper. The simplicity of the ignition system is due to the fact that the NH₄Cl/NaAlH₄ mixture reacts at ambient pressure and does not require pre-pressurization. The heat paper is used to spread heat throughout the pellet bed to facilitate nearly simultaneous reaction of all pellets. The composition of heat paper, manufactured by KDI Score, is proprietary, but it is assumed that it consists of a thermite formulation. The heat paper itself is most readily ignited by an electric match squib.

FILTER SYSTEM. The filter system consists of felt metal manufactured by the Brunswick Corporation. The felt metal is available in a variety of grades. A sequence of filters from very coarse to very fine has been found to act as a perfect filtration column. For the flow rates tested, clogging has not been experienced. A combination of three phenomena contributes to the simplicity of the filtration system: (1) the high diffusivity of hydrogen, (2) the physical properties of the solid residue and (3) the low temperature of the hydrogen generating reaction process.

The cannister itself can be made from a variety of materials which meet minimum requirements with respect to temperature resistance, mechanical and chemical integrity. For the purpose of test firings, a stainless steel prototype was used, fitted with pressure and temperature transducers (see Figure 5). A light-weight aluminum cannister can be employed for field use.

MATERIAL COMPATIBILITY. The FESS materials may consist of metallic, ceramic or organic materials. Some of these materials contain free and/or combined oxygen and carbon. Theoretically, hydrogen reacts with oxygen to form water and with carbon to form hydrocarbon, but these reactions usually require temperatures which are considerably higher than the tolerable maximum operational temperature determined for this program. Some reductions of hydrogen with protective oxide layers, e.g. CuO, may occur at lower temperature, but they would not impair the system. Another matter of concern may be hydrogen embrittlement. However, the hydrogen must first diffuse into the metallic materials before hydrogen embrittlement can occur. Since the diffusion process is slow, system deterioration will not occur during operation time.

SAFETY HAZARDS. Hydrogen can react with oxygen (air) and form water according to the equation:



Therefore, some precautions are required in dealing with hydrogen gas. Hydrogen hazards are listed in Table 4 together with data for methane and gasoline (see reference 8). According to Table 4 a hydrogen/air mixture is flammable within the region of 4.0 - 75.0 vol % and requires only 0.02 mJoule for ignition. Furthermore, hydrogen/air mixtures within the range 18.3 - 59.0 vol % may transit into a detonation, if the physical dimension of the mixture exceeds the inductance distance (L/D).

PROTOTYPE TEST GENERATOR AND PERFORMANCE CHARACTERISTICS

During the course of this program, 25 breadboard gas generators were designed and fabricated for test purposes at NSWC, Indian Head. The test generators were designed to meet the flow requirements for the FESS power supply. Heavy duty hardware was used in this design for safety reasons. However, it should be understood that such heavy duty hardware can easily be replaced by aluminum or other lightweight materials.

The first series of test firings were performed in early 1977 and investigated the application of the $\text{NH}_4\text{Cl}/\text{LiAlH}_4$ formulation. This test series utilized a standard neutral-burning grain design (tubular) consisting of a right-cylinder 30.48 mm (1.2") in diameter with a 12.7 mm (1/2") perforation. All grains tested for this program were formed from a reactant consisting of $2\text{LiAlH}_4/\text{NH}_4\text{Cl} + 5 \text{ Wt. \%}$ of Kraton binder +5 wt % of either NiAcAc or Fe_2O_3 catalyst. The grains were pressed at 20.25 MPa (3000 psi) in the mold fabricated for this program. Each grain was approximately 38.1 mm (1 1/2") in height and 30.48 mm (1.2") in diameter. To achieve the various lengths required, the grains were bonded to one another with Kraton. To achieve the flow rate required, a length of 508 mm (20") was necessary. The end of each cylinder was also inhibited with Kraton. It was obvious that this laboratory design was unacceptable for a full-up FESS system, but it was useful for examining the five requirements, and at the same time was the most economical to build.

To achieve the rapid rise time required, two techniques were attempted. The first and most obvious was to tie a small bag of powdered gas generator reactant (~20 g) to the electric match squib igniter. While this technique reduced delay times, it did not achieve delays as low as 25 ms. Assuming that an igniter producing non-hydrogen gaseous products is acceptable to this program, BKN_3 was then tried. Using this approach, rise times on the order of 100 ms were achieved, still somewhat short of the 25 ms required.

The data generated in this first series of test firings are presented in Table 5. Two different types of reactants were tested in this series, one containing NiAcAc as the catalyst, the second containing Fe_2O_3 . As can be seen from the data, burning rates can be nearly doubled by changing catalysts. Peak operating pressures were varied on purpose, using different nozzles or

different grain lengths, because we understood that the 3.38 MPa (500 psi) pressure, as specified at that time, might be modified to 5.4 MPa (800 psi), as it eventually was. Hence our desire, at this time, was to demonstrate operational capability at a variety of pressures. Pressure-time traces of several firings at various pressures are shown in Figures 6, 7 and 8. The gas stream temperatures, where available, were recorded just downstream of the filter before the nozzle. The test generator is shown in Figure 5. Gas volume and flow rate data were collected on a Collins gasometer.

From this first series of test firings, it appeared that no serious barriers would prevent the hydrogen gas generator from meeting all five requirements. However, two problem areas required investigation.

1. Reducing the rise time to < 25 ms
2. Devising a pelletized grain design to achieve required mass flow rates and burn times while utilizing a practical sized cannister.

The first of these problem areas, reduced delay time, was resolved by slightly modifying the cannister design, and by utilizing 5 g charges of BKNO_3 to rapidly pressurize the cannister. Heat paper was used to promote rapid ignition of all pellets in the cannister volume. As can be seen from Table 6, ignition delay was about 25 ms for all 14 test firings.

Area 2 was resolved by pelletizing the $\text{NH}_4\text{Cl}/\text{NaAlH}_4$ formulation discussed earlier. One further problem, that arose during the course of these test firings, was that of overlong burn time (7 seconds as opposed to the required 5 seconds). Strand burning experiments determined a burning rate of 0.025 in/sec for this formulation. Thus, pellets 12.7 mm (0.500") in diameter and 0.64 mm (0.025") thick were fabricated at pressures in excess of 33.75 MPa (5000 psi). These pellets should have yielded burn times on the order of 5 seconds. However, as can be seen from Table 6, the average burn time was about 7 seconds at ambient temperatures, meaning the actual burning rate was only 0.42 mm/sec (0.0167 in/sec). This lower rate can easily be offset in future designs by simply decreasing the pellet thickness from 6.35 mm (0.250") to 4.24 (0.167") to achieve the desired burn time of 5 seconds.

In addition to the 8 firings performed at ambient temperatures, 3 firings were made at -53.8°C (-65°F) and 3 firings at 93.3°C ($+200^\circ\text{F}$). These firings show a definite temperature dependency of burning rate. However, performance is acceptable in all six firings. Pressure-time traces at each temperature are shown in Figures 9, 10 and 11. Variations in performance data from units fired at the same temperature may be attributable to batch to batch variations in both the NaAlH_4 used, and the actual mixes manufactured using the various lots of NaAlH_4 . As described earlier, three separate mixes were required

to collect reactants necessary for the test program. It is logical to assume that each of these mixes would yield a slightly different performance. In actual usage, the batches could be blended or one large batch could be manufactured.

RECOMMENDATIONS

It is apparent from the preceding that the hydrogen gas generator can serve as a practical power supply for the FESS program. The five requirements can be met, and if these requirements should change, the hydrogen gas generator is flexible enough to meet these as well. The next logical step would be to begin interfacing the hydrogen gas generator with an actual fluidic system to see what problems might be encountered. Once these problems have been surmounted, design of an actual power supply system can be initiated.

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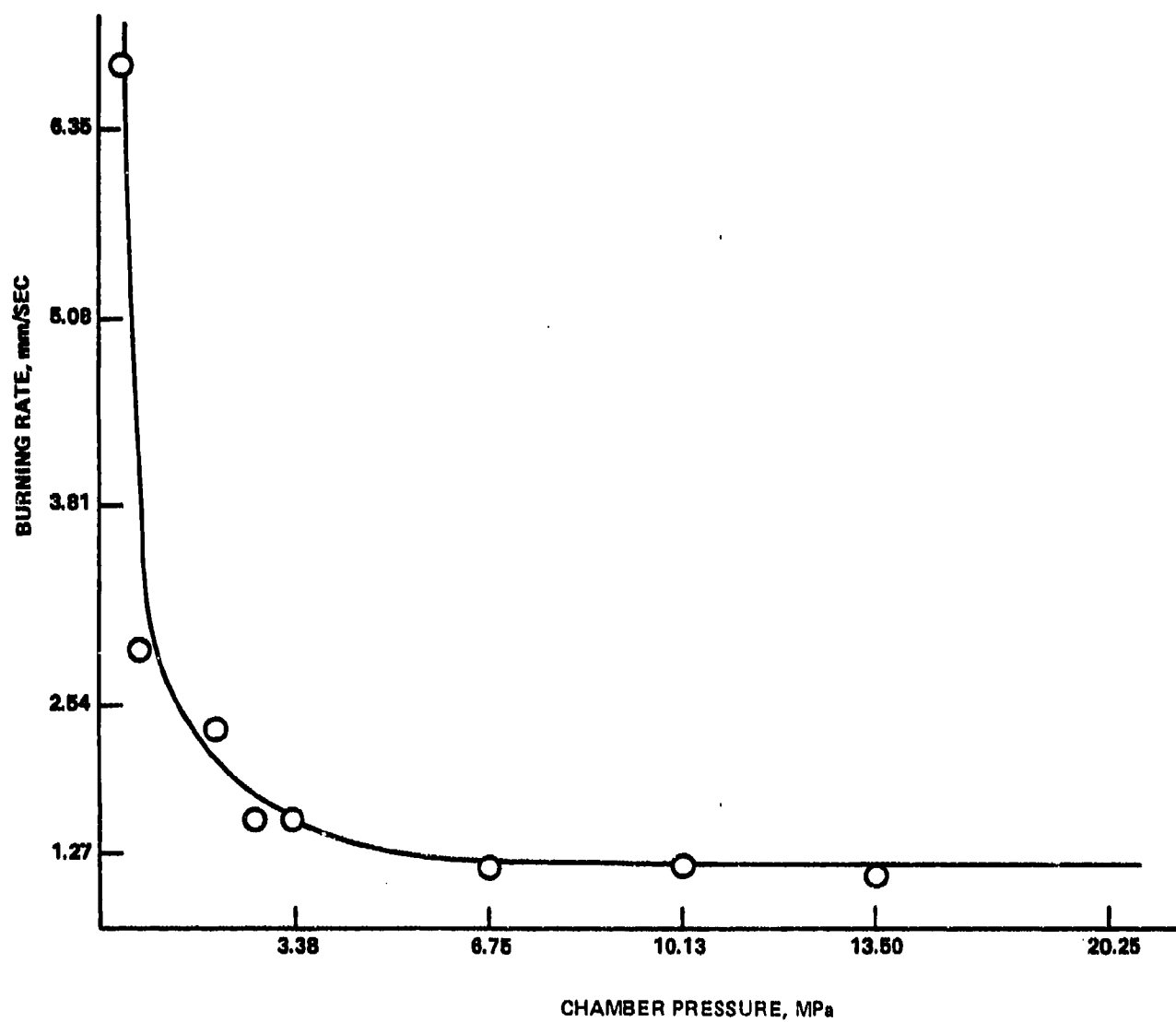


FIGURE 1 BURNING RATE VS. CHAMBER PRESSURE $2\text{LiAlH}_4/\text{NH}_4\text{Cl}$

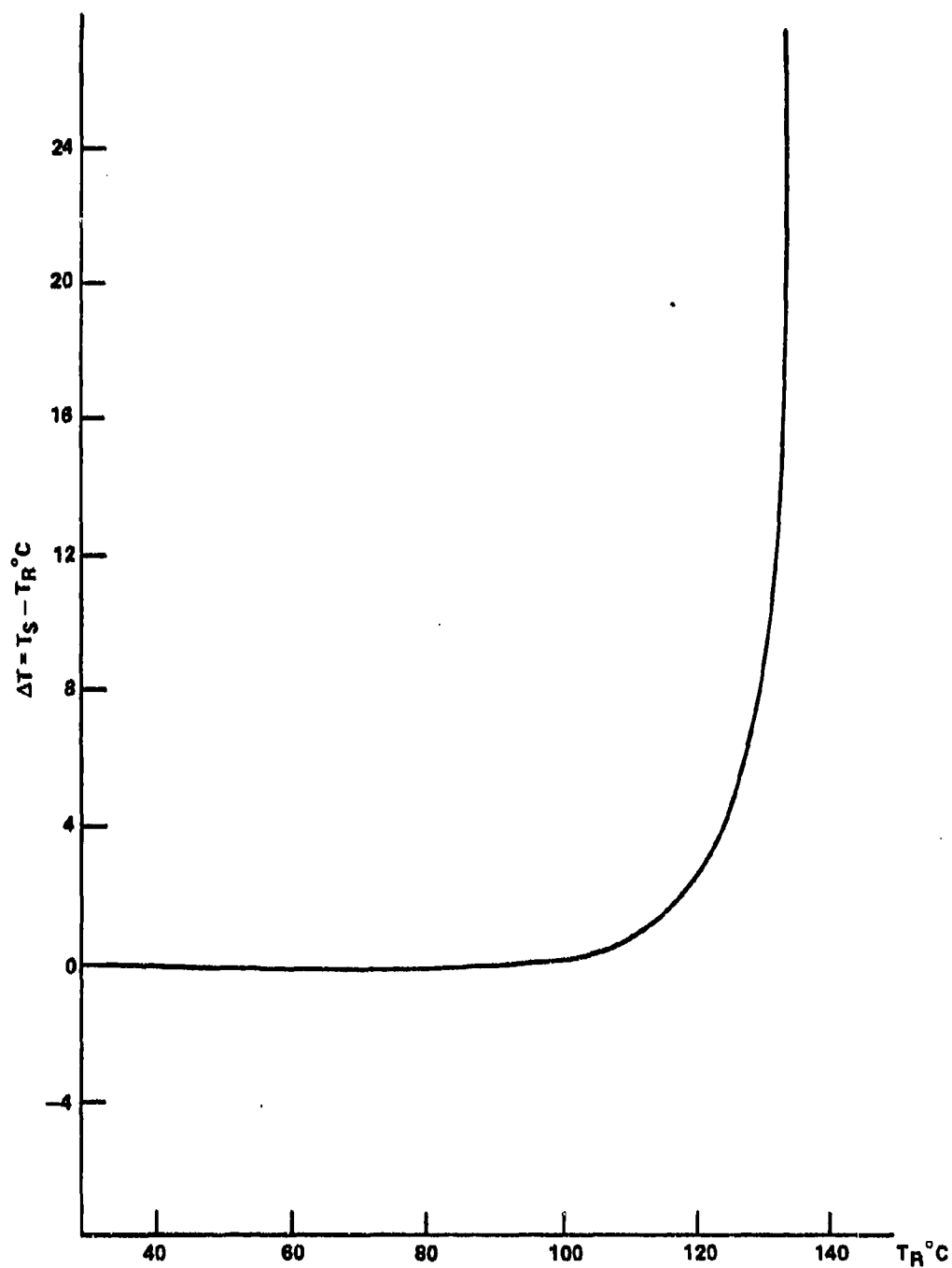


FIGURE 2 DTA ON 1LiAlH₄/1NH₄Cl IN N₂ (PEAK AT 135°C, HEATING RATE 1°C/MIN)

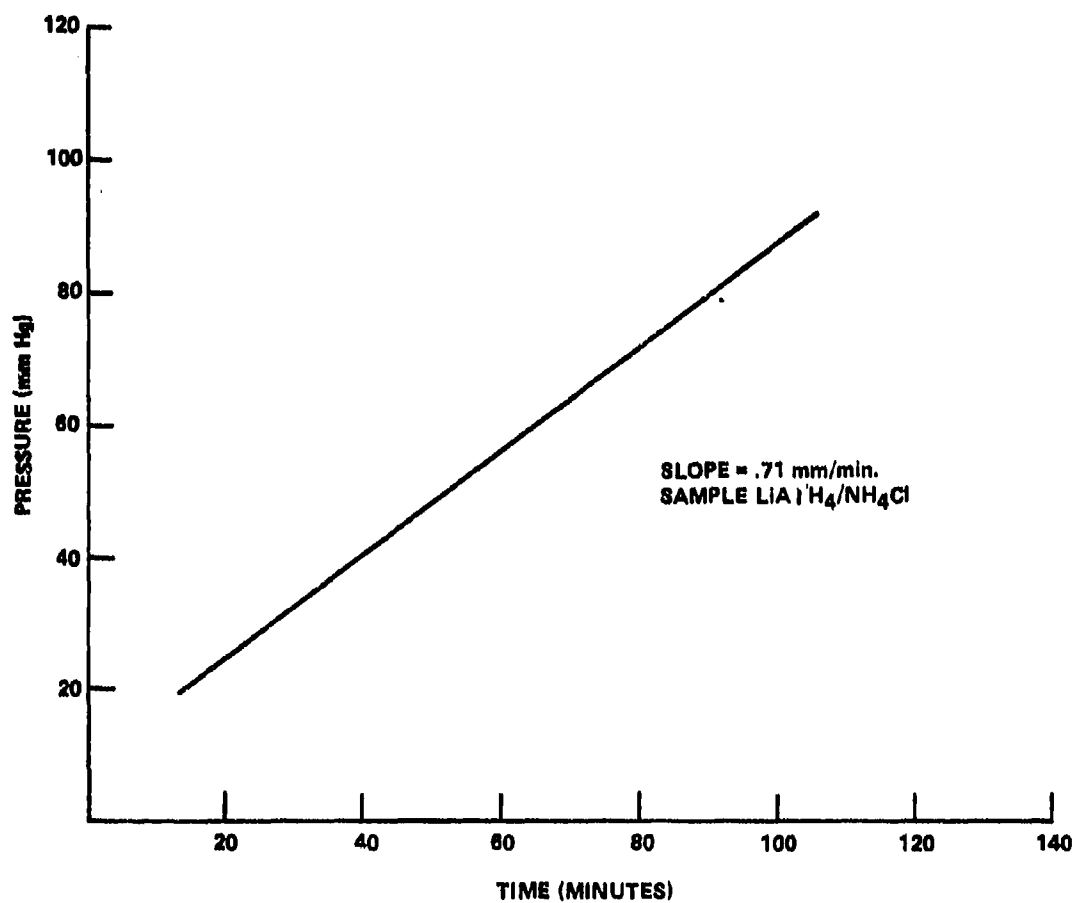


FIGURE 3 TALIANI: TEST AT 72°C IN N₂

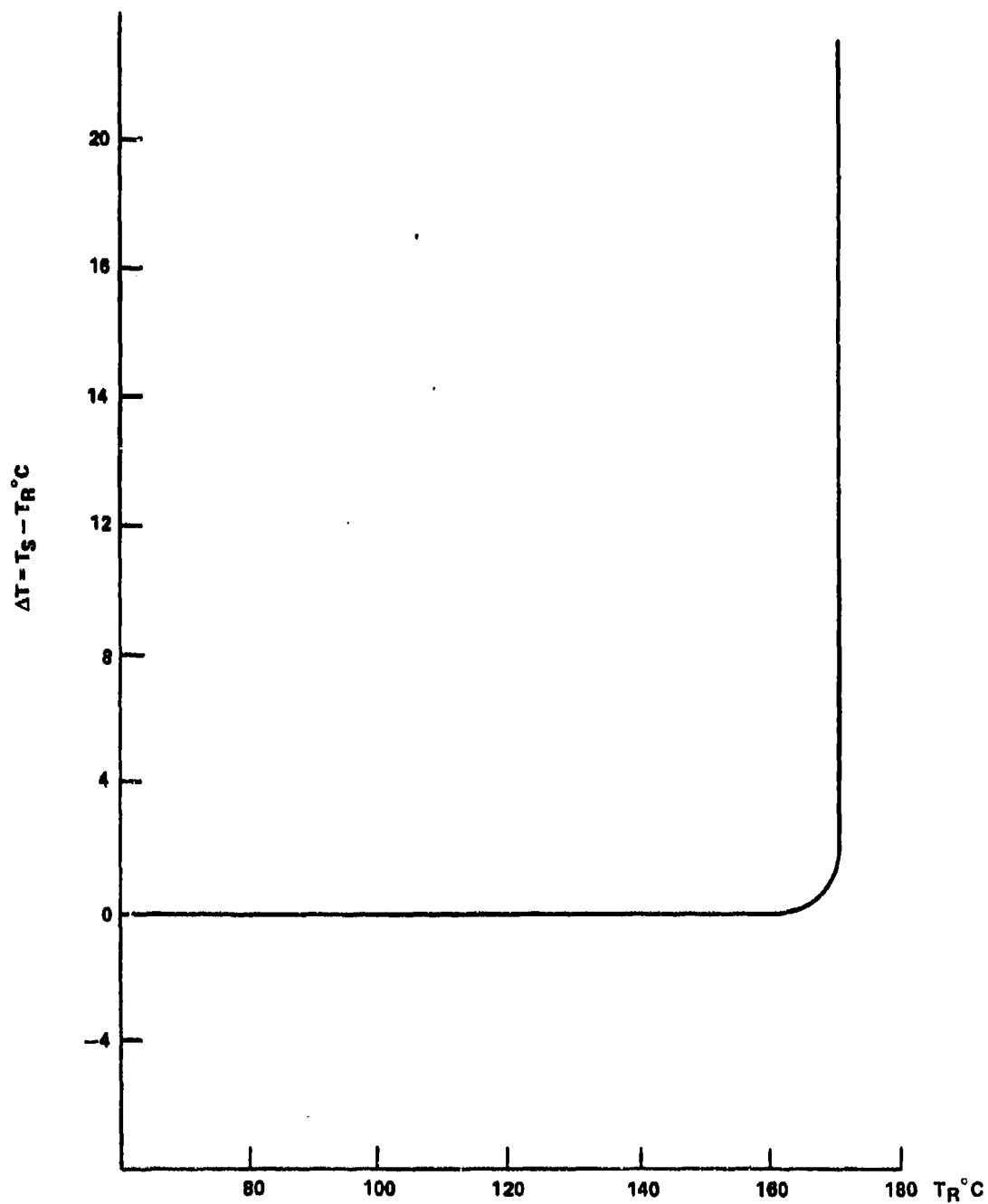


FIGURE 4 DTA ON 1NaAlH₄/1NH₄Cl IN N₂ (PEAK AT 172.5°C, HEATING RATE 1°C/MIN)

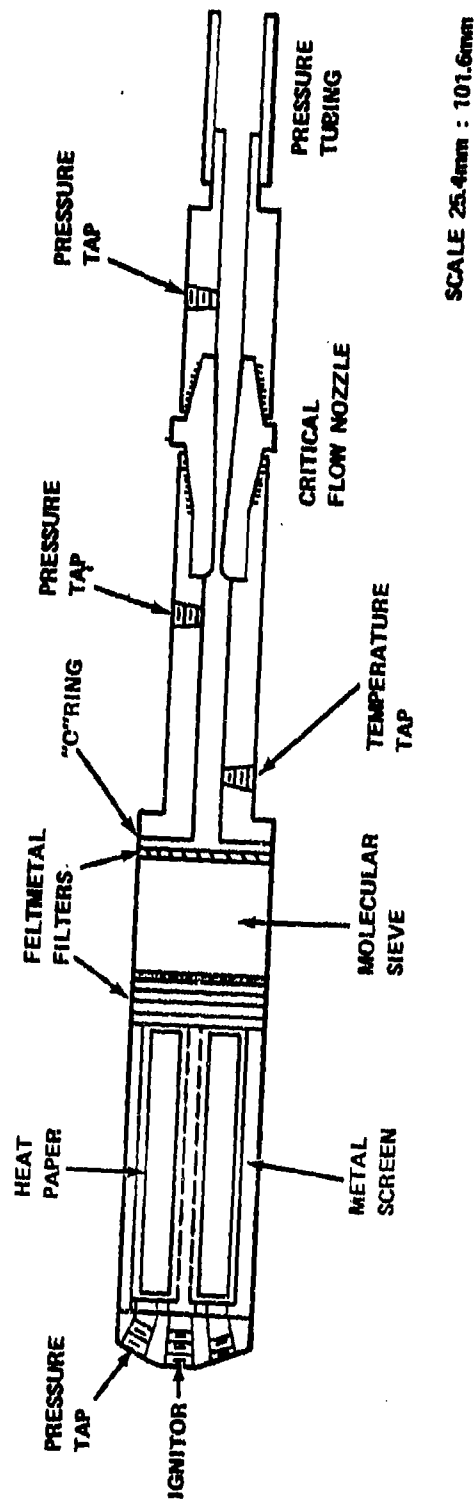


FIGURE 5 TEST FIXTURE FOR H₂ GAS GENERATOR

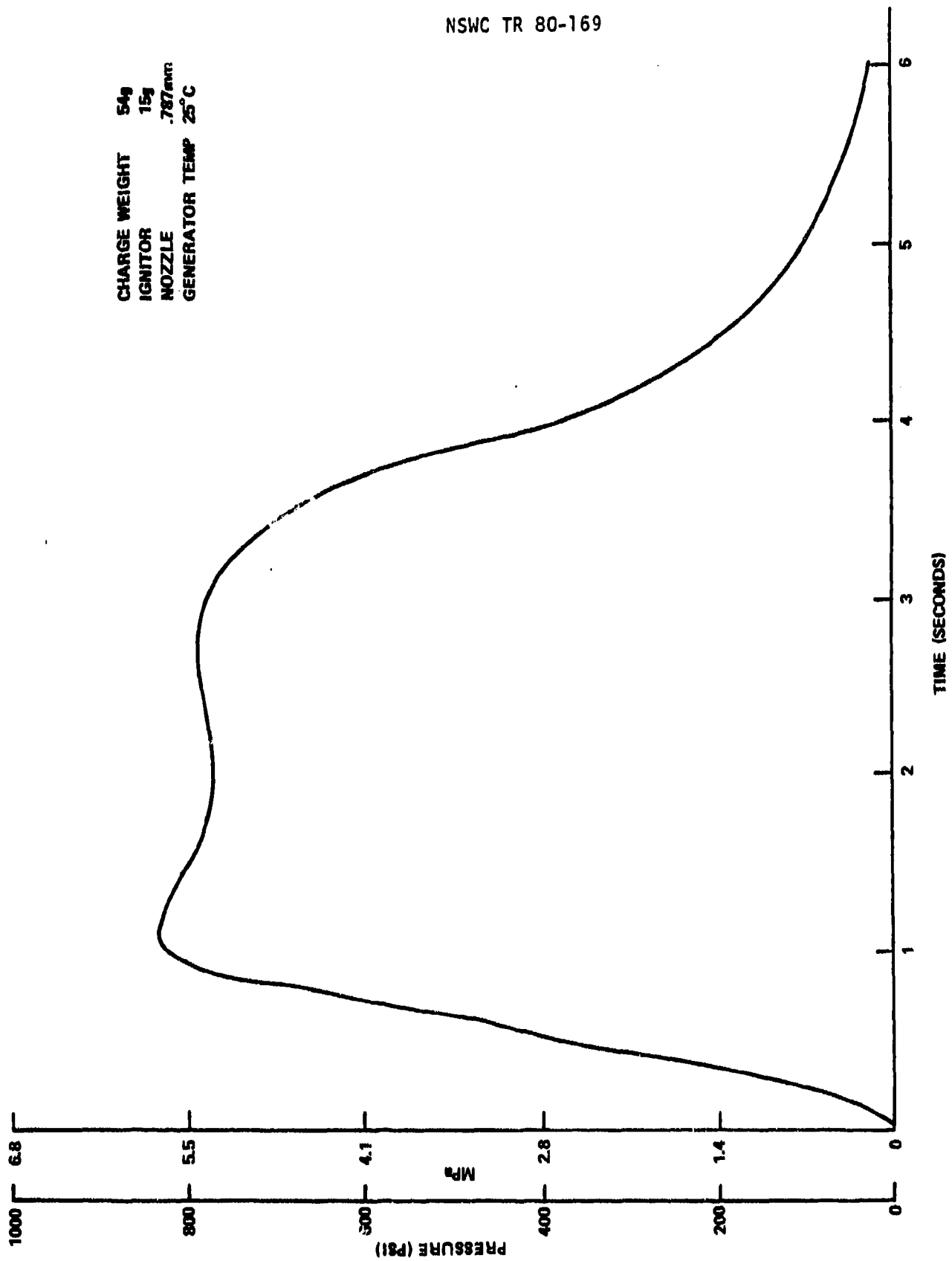


FIGURE 6 PRESSURE TRACE FOR CYLINDRICAL HGG (FROM FIRING #4 IN TABLE 5)

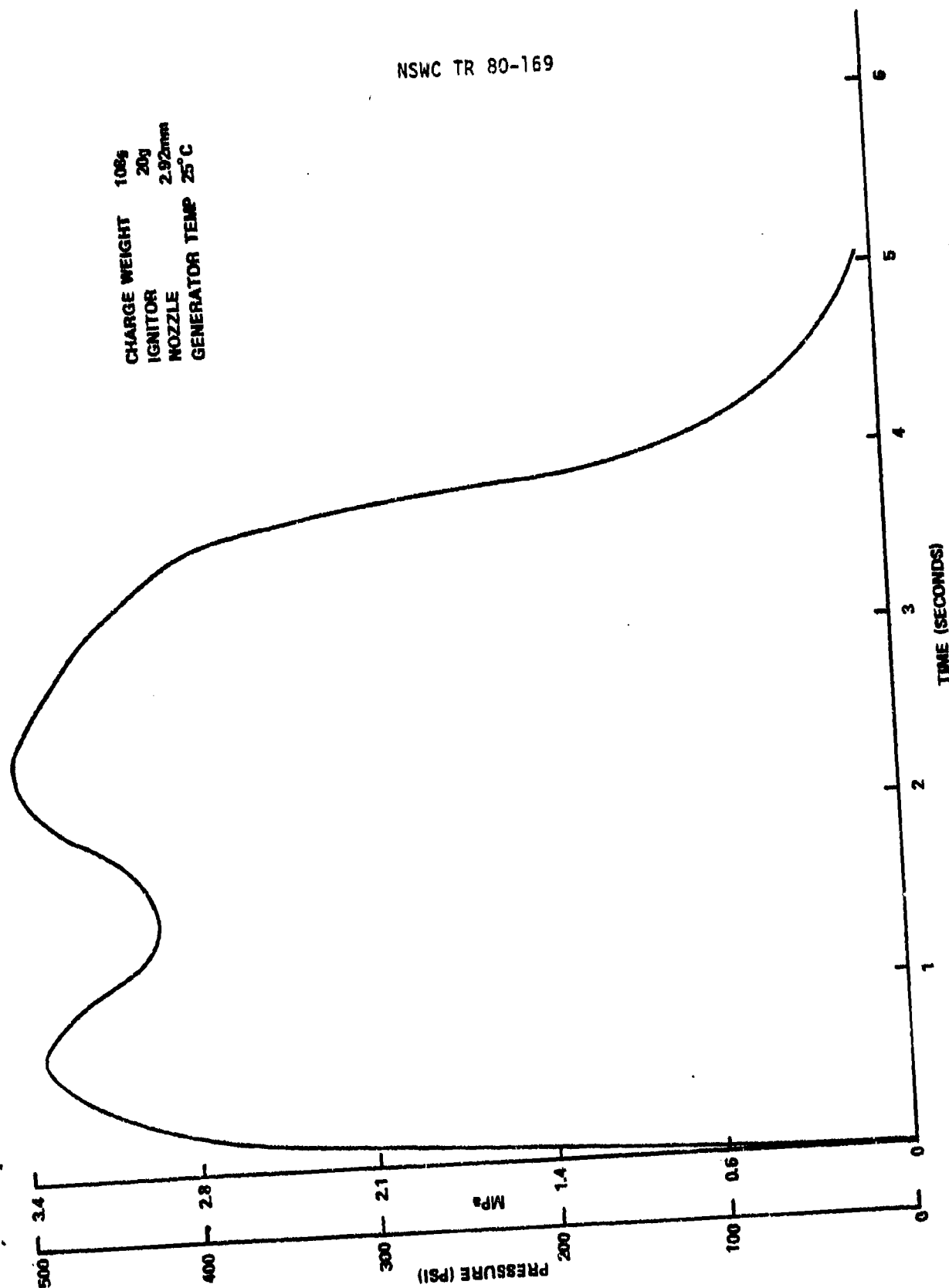


FIGURE 7 PRESSURE TRACE FOR CYLINDRICAL HGG (FROM FIRING #5 IN TABLE 5)

CHARGE WEIGHT 87g
IGNITOR 7g
NOZZLE 1.78mm
GENERATOR TEMP 25°C

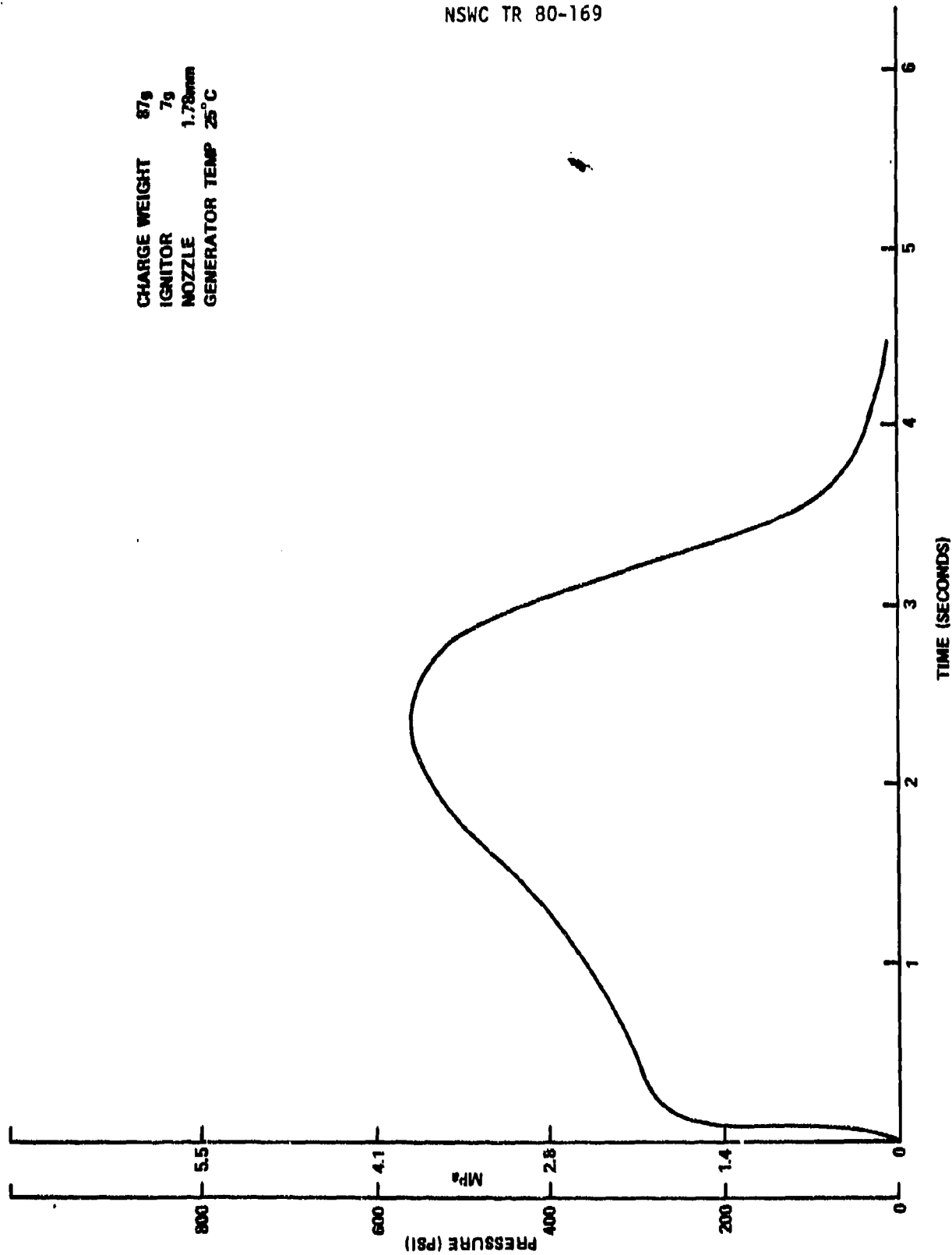


FIGURE 8 PRESSURE TRACE FOR CLINDRICAL HGG (FROM FIRING #11 IN TABLE 5)

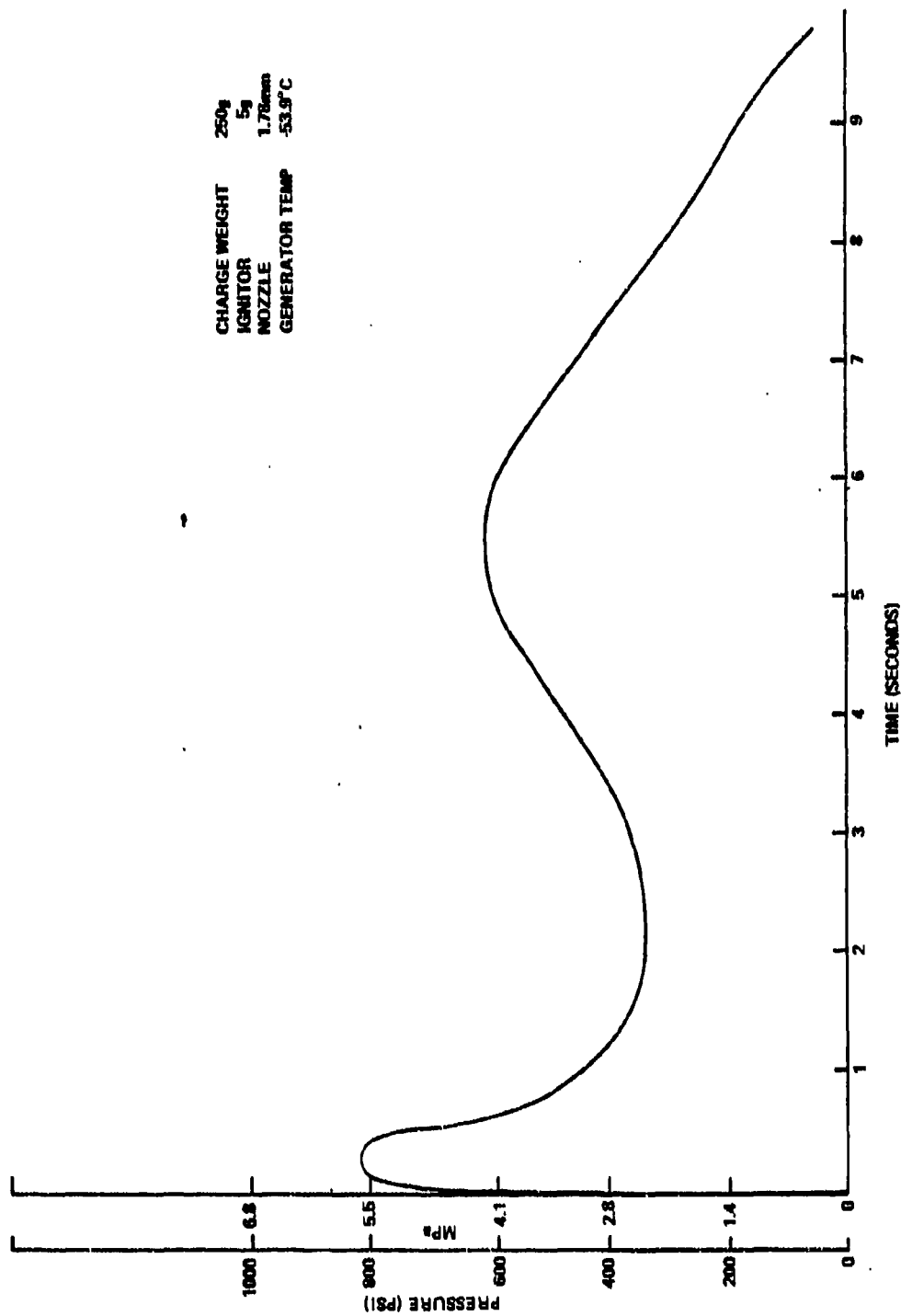


FIGURE 9 PRESSURE TRACE FOR PELLETIZED HGG (FROM FIRING #7 IN TABLE 6)

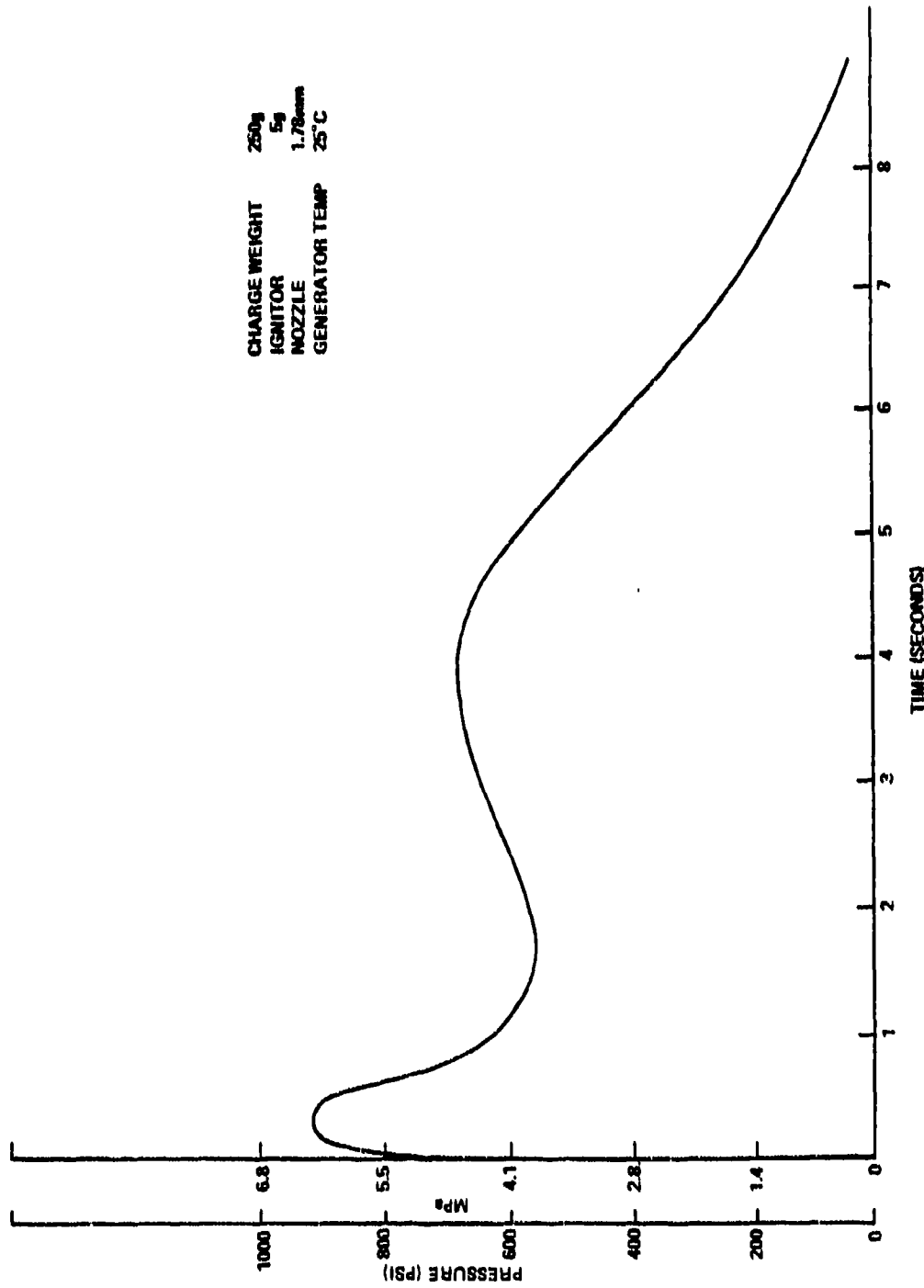


FIGURE 10 PRESSURE TRACE FROM PELLETIZED HGG (FROM FIRING #13 IN TABLE 6)

CHARGE WEIGHT 250g
IGNITOR 5g
NOZZLE 1.78mm
GENERATOR TEMP 93.3°C

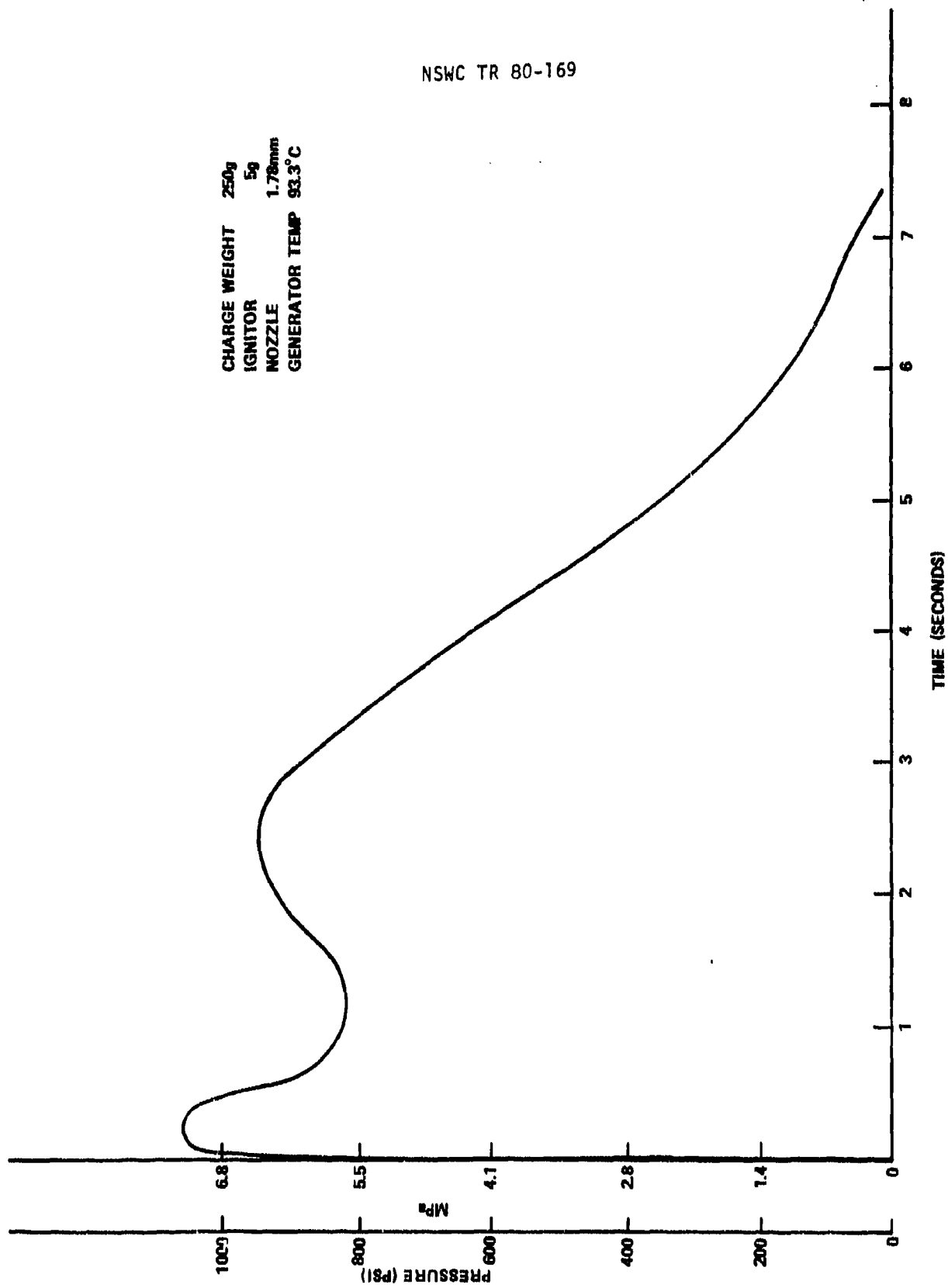


FIGURE 11 PRESSURE TRACE FROM PELLETIZED HGG (FROM FIRING #10 IN TABLE VI)

Table 1 Reactions of Ammonium Chloride with Metal Hydrides

Compositions (moles)	Yield, 1/g	ΔH_f° Kcal/mole H_2	Calculated Exhaust gas Temp., $^\circ K$
$1NH_4Cl + 1 NaAlH_4$	0.8	-15.2	1074
$1NH_4Cl + 1 NaAlH_4 + 1LiAlH_4$	0.8	- 8.9	683
$1NH_4Cl + 1 NaAlH_4 + 2LiAlH_4$	0.8	- 6.4	499
$1NH_4Cl + 1 NaAlH_4 + 3LiAlH_4$	0.7	- 4.7	384
$1NH_4Cl + 1 NaAlH_4 + 4LiAlH_4$	0.5	- 3.5	-
$1NH_4Cl + 1 LiAlH_4$	0.8	-13.45	1070
$1NH_4Cl + 2 LiAlH_4$	0.9	- 8.9	826
$1NH_4Cl + 3 LiAlH_4$	0.8	- 6.4	675

Table 2 Hydrogen Gas Generator Safety Data

A. $2\text{LiAlH}_4/\text{1NH}_4\text{Cl}$

Formulation

51 wt% LiAlH_4

39 wt% NH_4Cl

5 wt% Burning rate modifier (Fe_2O_3)

Safety Tests

Sliding friction: 320 lbs (M)

Impact: 100 mm/5kg (M)

Electrostatic discharge: 0.0125 joules (M)

B. $1\text{NaAlH}_4/\text{1NH}_4\text{Cl}$

Formulation

45.2 wt% NaAlH_4

44.8 wt% NH_4Cl

5 wt% Burning rate modifier (Fe_2O_3)

5 wt% Binder (Kraton)

Safety Tests

Sliding friction 750 lbs (L)

Impact: 275 mm/5kg (M)

Electrostatic: 0.50 joules (M)

Table 3 Cost of Hydrogen Gas Generator
Ingredients (in Dollars per Pound)

<u>Material</u>	<u>Price</u>
NH_4Cl	.75
LiAlH_4^*	32.00
$\text{NaAlH}_4^{*\#}$	79.00
NaBH_4	13.50

*Costs are high because of low-volume production

#Estimated price for large scale production 1\$
per lb.

Table 4 Hazard Data of Hydrogen, Methane and Gasoline

Sample	Hydrogen	Methane	Gasoline
Limits of flammability in air, vol. %	4.0 to 75.0	5.3 to 15.0	1.0 to 7.6
Limits of detonability in air, vol. %	18.3 to 59.0	6.3 to 13.5	1.1 to 3.3
Stoichiometric composition in air, vol. %	29.53	9.48	1.76
Minimum energy for ignition in air, mJ	0.02	0.29	0.24
Autoignition temperature, K	858	813	501 to 744
Flame temperature in air, K	2318	2148	2470
Percentage of thermal energy radiated from flame to surrounding, %	17 to 25	23 to 33	30 to 42
Burning velocity in NTP air, cm/s	265 to 325	37 to 45	37 to 43
Detonation velocity in NTP air, km/s	1.48 to 2.15	1.39 to 1.64	1.4 to 1.7
Maximum experimental safe gap in NTP air, cm	0.008	0.12	0.07
Detonation induction distance in NTP air	L/D=100	-	-
Limiting oxygen index, vol. %	5.0	12.1	11.6
Vaporization rates (steady state) of liquid pools without burning, cm/min	2.5 to 5.0	0.05 to 0.5	0.005 to 0.02
Burning rates of spilled liquid pools, cm/min	3.0 to 6.6	0.3 to 1.2	0.2 to 0.9
Flask point, K	gaseous	gaseous	≈230
Toxicity	nontoxic (asphyxiant)	nontoxic (asphyxiant)	slight (asphyxiant)
Energy of explosior. (g TNT)/(g fuel)	≈24	≈11	≈10
Energy of explosion, (g TNT)/(cm ³ NBP liquid fuel)	1.71	4.56	7.04
Energy of explosion, (kg TNT)/(m ³ NTP gaseous fuel)	2.02	7.03	44.22

NBP = Normal boiling point

NTP = 1 atm and 20°C (293.15°K).

Table 5 Hydrogen Gas Generator - Evaluation Test Data

No.	Catalyst	Charge Weight (g)	Ignitor Weight (g)	Charge Length (mm)	Nozzle Diameter (mm)	Ignition Delay (sec)
1	Ni AcAc	88	5	155.7	1.78	1.4
2	Ni AcAc	86	8	152.4	1.78	1.2
3	Ni AcAc	63	10	106.7	0.79	1.0
4	Ni AcAc	54	15	96.5	0.79	0.27
5	Ni AcAc	108	20	180.3	2.92	0.10
6	Fe ₂ O ₃	90	20	152.4	0.79	0.20
7	Fe ₂ O ₃	91	20	152.4	0.79	0.20
8	Ni AcAc	270	20	457.2	2.92	0.20
9	Ni AcAc	301	20	508.0	6.22	0.10
10	Fe ₂ O ₃	298	20	762.0	1.78	0.10
11	Ni AcAc	87	7	154.9	1.78	0.10

No.	Maximum Pressure (MPa)	Burn Time (sec)	Maximum Temperature (°C)	Total Gas Volume (liters)	Flow Rate (g/sec)	Burning Rate (mm/sec)
1	4.83	5.0	NA	90.7	1.11	1.40
2	4.98	3.9	NA	98.8	1.15	1.32
3	5.02	4.6	113.3	43.2	0.85	1.07
4	5.73	4.6	127.2	43.5	0.90	1.09
5	3.51	4.1	NA	113.0	1.5	1.22
6	2.44	12.3	81.7	91.6	0.66	0.53
7	2.71	13.0	110	91	0.65	0.53
8	2.78	5.9	96.1	NA	4.20	NA
9	0.79	5.9	63.3	NA	4.21	NA
10	4.07	11.9	62.3	NA	2.44	NA
11	3.75	3.5	NA	86.1	1.23	1.37

Table 6 Hydrogen Gas Generator - Temperature Qualification Test Data

No.	Charge Weight (g)	Ignitor Weight (g)	Nozzle Diameter (mm)	Ignition Delay (msec)	Test Generator Temperature (°C)
1	250	5	0.762	25	Ambient (25)
2	250	5	1.19	25	25
3	250	5	1.78	25	25
4	250	5	1.78	25	25
5	250	5	1.78	25	25
6	250	5	1.78	25	-53.9
7	250	5	1.78	25	-53.9
8	250	5	1.78	25	-53.9
9	250	5	1.78	25	93.3
10	250	5	1.78	25	93.3
11	250	5	1.78	25	93.3
12	250	5	1.78	25	25
13	250	5	1.78	25	25
14	250	5	1.78	25	25

Table 6 (Cont) Hydrogen Gas Generator - Temperature Qualification Test Data

No.	Maximum Pressure (MPa)	Burn Time (sec)	Maximum Temperature (°C)	Total Gas Volume (liters)	Flow Rate (l/sec)	Burning Rate (mm/sec)
1	17.89	NA	NA	NA	18.1	NA
2	11.22	7.2	153.3	175.2	21.5	0.44
3	5.84	7.2	88.9	180.7	24.2	0.50
4	6.27	7.2	100	184.3	24.0	0.45
5	6.12	7.4	NA	176.1	22.8	0.47
6	5.17	10.0	112.1	188.8	18.7	0.32
7	4.44	7.7	NA	193.7	21.7	0.39
8	3.70	8.4	NA	190.7	19.8	0.38
9	9.48	4.7	226.7	189.1	43.0	0.54
10	6.64	5.0	NA	191.4	35.8	0.52
11	7.32	4.8	NA	192.4	38.8	0.50
12	7.88	5.8	77.8	193.0	33.9	0.45
13	5.06	6.3	NA	188.2	26.3	0.39
14	4.68	7.0	NA	191.7	24.6	0.37

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